

Review Article

Brazilian soils: A 40-year review on earthworms, enchytraeids, collembolans and soil mites

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Abstract

Introduction: Brazil, with 846 million hectares, struggles to manage its varied environmental landscape, as 60% is used for farming, affecting soil ecosystems that rely on organisms for nutrient cycling and water infiltration. The diversity of these organisms is influenced by land use, rainfall, temperature, and humidity. Establishing Specific Protection Goals (SPGs) for pesticides is essential, considering their Normal Operating Range in agricultural ecosystems. A literature review on the biodiversity of earthworms, enchytraeids, springtails, and soil mites in Brazil examined their abundance in relation to abiotic factors.

Methods: A systematic literature search was conducted across 11 specialized databases and Google Scholar, retrieving 120 peer-reviewed Brazilian field trials up to June 2023, and applying strict inclusion criteria and descriptive statistical analysis on standardized density data. The associations between organism density and factors such as season, organic matter percentage, pH, and tillage were evaluated.

Results: Results showed that soil mites were the most studied group (>40%), followed by earthworms, springtails, and enchytraeids. Tillage generally reduced organism density, and both Collembola and soil mites showed lower densities in the dry season compared to the rainy season. Collembola and mite densities also varied with soil pH, whereas earthworms were pH independent.

Conclusions: The study shows that soil fauna densities in Brazil vary widely with land use, soil type, season, and farming practices—particularly tillage—yet significant gaps remain in regional coverage and methodological consistency, underscoring the need for harmonized research and collaborative efforts to inform soil biodiversity management and ecosystem service-oriented policies.

Key words: Biodiversity review, Brazilian ecosystems, soil fauna



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Introduction

Over the last 50 years, humans have altered ecosystems more rapidly and extensively than at any other point in history (Millennium Ecosystem Assessment 2005). The transformation of forests into agricultural land has placed significant pressure on both aquatic and terrestrial ecosystems (Prado et al. 2016).

While this transformation has led to negative impacts, it has also contributed to global population growth by supplying food and other biomass-derived products (Barretto et al. 2013). Soil organisms play a crucial functional role in soil ecosystems (Lee 1985). They contribute to provisioning ecosystem services by facilitating nutrient turnover and water cycling (Millennium Ecosystem Assessment 2005), and therefore they have remarkable agronomical and societal relevance.

The ecosystem service approach has its roots in concepts developed during the late 1960s and throughout the 1970s, which emphasized the societal value of nature's functions (Hermann et al. 2011). In Brazil, various pressures impact soil ecosystem services, including erosion, soil contamination, reduced soil fertility and biodiversity, and a decline in carbon stocks (Prado et al. 2016). Although soil conservation was not historically prioritized in government agendas (Guerra et al. 2014), numerous agricultural production systems aimed at preserving soil have been developed and implemented in Brazil in recent decades. In commodity-producing regions, certain management systems have gained prominence, such as no-tillage, crop-livestock integration, and crop-livestock-forest integration (Muniz et al. 2011). Meanwhile, in other regions, family farmers are adopting new integrated systems like organic farming and agroforestry (Martinelli et al. 2010; Prado et al. 2016).

As one of the largest producers and exporters of bioenergy, food, and fiber, Brazil plays a key role in global agriculture (OECD-FAO 2017; Silva et al. 2020). At the same time, the country holds vast natural areas and some of the highest biodiversity levels globally (M.C.T.I. 2016). However, three crops—soybean, corn, and sugarcane—used for both food and bioenergy production occupy more than three-quarters of the country's cropland and harvested area (Novaes et al. 2022).

Globally, soils are estimated to host between 40% and 60% of all described species (Winding et al. 2020; Anthony et al. 2023), making them one of the most significant yet underexplored biological frontiers (Geisen et al. 2019). Neotropical regions, such as Brazil, are especially rich in biodiversity and contain numerous endangered hotspots (Myers et al. 2000). The soil ecosystems in these regions support a diverse community of soil organisms, which play a crucial role in ecosystem functioning. Soil organisms may underpin essential ecosystem services such as crop production, biological pest control, nutrient cycling, seed dispersal, pollination, water storage, availability, pedogenesis, soil erosion control, and carbon sequestration (Brown et al. 2024). The structure and abundance of soil macrofauna communities are highly responsive to the management of soil and plant cover (Lavelle et al. 1992).

In the Peruvian Amazon, Lavelle and Pashanashi (1988) observed significant changes in both the biomass and diversity of soil macrofauna following the establishment of pastures and annual crops. This pattern has been replicated at various tropical sites, where annual cropping systems generally result in a substantial reduction in soil fauna diversity and abundance. This decline occurs regardless of the crop species, primarily due to soil disturbance and the lack of permanent cover.

Soil and surface-litter dwelling macrofauna, which include larger, visible invertebrates, represent 23–27% of all described species (Decaëns et al. 2006). Due to the taxonomic challenges in identifying many soil-dwelling species (Decaëns et al. 2006), the overall richness and abundance of soil macroinvertebrates, especially in the tropics, remain poorly understood (Guerra et al. 2020).

These organisms play key roles in essential ecosystem services (Lavelle et al. 2006). Their sensitivity to land-use changes makes them valuable bioindicators of ecological stress (Lavelle et al. 2021), as well as potential indicators of soil quality and ecosystem service provision (Sofo et al. 2020). Brazil has a high number of sampling sites for soil macrofauna, though many studies remain unpublished or lack open-access data (e.g., Demetrio et al. 2020; Demetrio et al. 2021). Additionally, limited quantitative data on tropical soil macroinvertebrate sampling events can be found in the Global Biodiversity Information Facility (GBIF) database (Brown et al. 2024).

In agricultural landscapes, soil organism communities can be impacted by multiple stressors, such as tillage, fertilization, harvest, compaction, and pesticide application, which can lead to detrimental effects on soil functioning. To minimize the adverse impacts of these stressors on the soil faunal community, Brazil is currently undergoing a paradigm shift. Since 2019, the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) has been working on environmental risk assessment frameworks tailored to local conditions (Santos 2016). One of the main areas of focus for IBAMA concerns pesticide use and its potential impact on non-target organisms, as well as implications for pesticide registration.

The Brazilian regulation is currently transitioning from a hazard-based classification system to a prospective risk assessment approach. To define realistic protection goals for a new risk assessment framework for soil organisms, it is crucial to understand the normal operating range of soil organism communities in Brazilian landscapes, that is, the occurrence and variability of soil organisms in different habitats and the most relevant environmental factors, as well as the implications for soil functions and ecosystem services. When defining the ecological relevance of organism groups, as well as regulatory thresholds on acceptable effect magnitudes and durations for a prospective risk assessment approach, a good understanding of natural background variability, resilience, and impacts of stressors on soil organisms is needed under local Brazilian conditions.

Thus, the aim of this study was to conduct a comprehensive literature review on soil macrofauna abundance, focusing on earthworms, enchytraeids, collembolans, and soil mites, and assess the Normal Operating Range (NOR) for these species in terms of density, distribution, and variability across Brazil's different habitats. The impact of several abiotic factors, that is, soil properties (pH, organic matter content, soil type), land use, tillage intensity, and season, on the field abundances of soil organisms is evaluated. In contrast to the existing literature referenced in this study, this research seeks to enhance the understanding of the differences and similarities in the variability fluctuations among the four organism groups in relation to specific environmental parameters.

Methods

Literature search strategy

A literature search was conducted using STNext, an integrated platform that provides access to 100 databases covering both specialist and generalist sources. For this specific search, 11 databases were consulted, namely Medline, Agricola, Biosis, CABA, FSTA, Toxcenter, Pqscitech, Esbiobase, HCAPLUS, Embase,

Table 1. Details retrieved from each publication when available.

Category	Details retrieved within each category
Geography	Brazilian state; precise location (town)
Sampling	Date of sampling; season; rainy vs. dry season ⁵ ; sampling method ¹ , sampling area (m ²), volume (cm ³) and depth (cm)
Soil characteristics	Arable, grassland, natural cover ² ; organic matter content (%); soil pH; silt (%), sand (%), clay (%); soil classification (Brazilian and European Classification); alkalinity
Agricultural practices	Crop during sampling; tillage vs. no tillage; pesticide use and details
Taxonomy	Group ³ ; order; family; species
Density	Total density (n); average density per m ² + standard deviation; maximum and minimum density ⁴ ; Shanonn Diversity Index (H); Simpson Dominance Index (IS)

¹ Sampling methods consisted of the following options: Berlese funnel, chemical extraction, electric extraction, foliar collection, hand sorting, litter collection, litter bags, pitfall traps, soil cores, surface collection, traps, TSBF (Tropical Soil Biology and Fertility) or TSBF plus pitfall traps; ² Land occupation was classified as arable, grassland, or natural cover. Arable land includes all plots that were managed by humans and allocated to agriculture or forestry; ³ Organisms were artificially grouped as earthworms, springtails, soil mites, and enchytraeids; ⁴ Maximum and minimum densities are only considered if they are from the same study, same sampling method, and same organism group; ⁵ For each sampling location, dry versus rainy season was selected either based on the information provided in the publication or, when absent, on latitude and openly available online climate data.

and Scisearch. Additionally, the search was performed with Google Scholar to confirm additional publications not previously found in the aforementioned databases (e.g., Scopus, Web of Science, SciELO). The search included all existing publications up to June 2023 and focused solely on peer-reviewed field trials, excluding all duplicates and uniquely laboratory-based studies from the analysis. Likewise, master’s and doctoral theses were not included in this review due to the lack of a peer review process. The search terms (keywords) used for the review included names of the 26 states of Brazil and related keywords in both English and Portuguese, such as: “Oligochaeta,” “Earthworm,” “Minhoca,” “Enchytraeid,” “Enquitreídeo,” “Potworm,” “Mite,” “Ácaro,” “Soil,” “Solo,” “Field,” and “Campo.” Studies dealing only with taxonomy or systematics were excluded from further analysis due to the lack of data on abundance for specific organisms. In total, more than 120 peer-reviewed publications were retrieved from the literature search. From these, due to unreliable data or lack of relevant information, only 102 publications were used for the data analysis. All 102 evaluated publications are detailed in the list of references; however, from the 102 publications, due to the different filters used for the data evaluation, some of these publications were not considered (n = 22; for more details, please see Suppl. material 1).

From the retrieved publications, the following details (when available) were summarized into a spreadsheet for data analysis (Table 1).

Data analysis

Descriptive statistical analysis was performed to evaluate the association of several parameters with the density of the various organism groups—earthworms, springtails, soil mites, and enchytraeids. The following parameters were evaluated: Brazilian state, soil organic matter (OM) content, seasonal variation (dry versus rainy season), tillage, soil pH, land use (arable, grassland, or natural cover), and type of soil (according to Brazilian classification). Average densities are presented in the Results and Discussion section together with standard deviations (± SD). Standard deviations are calculated based on all studies used for that specific comparison and are not

individually study related. Microsoft® Excel® for Microsoft 365 MSO (Version 2403 Build 16.0.17425.20236) was used for the descriptive statistical analysis and graphic presentation. No detailed significance evaluation was performed on the results, as the data originated from 102 different studies. Given the variations identified among the publications concerning environmental changes, sampling differences, and methodologies employed, no statistical significance analyses were conducted. Furthermore, the limited number of studies that met identical conditions resulted in insufficient statistical power to undertake more advanced statistical evaluations.

The following parameters were chosen for data analysis, namely: land use, seasonal variation, type of soil (Brazilian classification), soil pH, OM content, and agricultural practices. For all of them, for the analysis of average density (number of individuals m^{-2}) variation according to land use and seasonal variation, only studies where sampling occurred in sites where no pesticides or fertilizers were used were considered. In addition, only studies where the sampling method was chemical extraction, electric extraction, hand sorting, soil cores, TSBF (Tropical Soil Biology and Fertility Method—ISO 23611-5:2011), or TSBF plus soil cores were considered.

Discrepancies among studies concerning sampling methods, sampled areas, depths, and other parameters were standardized based on an “area” measurement. All data were converted to a basis of individuals per square meter (m^2). For this evaluation, only studies that provided specific details regarding the number of individuals per sampling area or both measurements separately were included. Results that were ambiguous or imprecise concerning the sampling area were excluded from the analysis.

Type of soil

The soils were classified as in the respective publication and followed the classification from the Sistema Brasileiro de Classificação de Solos (SiBCS) developed by Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA). Only studies where the type of soil was specified were considered. The original Brazilian nomenclature was kept for the soil type classification, as additional information (not available in some publications) would be required for the translation into the World Reference Base for Soil Resources (WRB) system.

pH in arable fields and grassland

For this parameter, the reference values were grouped in categories of pH intervals of 0.5 units (e.g., pH 6.5–7.0) to allow for better graphic representation. Only studies with fields where no tillage occurred and where the pH value was specified were considered for the evaluation.

Organic matter in arable fields and grassland

For this parameter, the reference values were grouped in batches (e.g., organic matter 6.5–7.0) to allow for better graphic representation. For the organic matter evaluation, only studies with fields where no tillage occurred were considered. Only studies where the percentage of organic matter was specified were included.

Agricultural practices—tillage in arable fields

For this evaluation, only studies where the occurrence of tillage or no tillage was specified were considered.

Please refer to Suppl. material 1 for details on the studies considered in these analyses.

Results and discussion

Recent data indicate a significant increase in research focused on the biodiversity of soil organisms in Brazil over the past few years. Specifically, in terms of studies that provide density values for various organism groups—excluding those dedicated solely to taxonomy and systematics—only 10 studies were identified between 1982 and 1999. In contrast, the subsequent periods yielded 34 studies from 2000 to 2009, 39 studies from 2010 to 2019, and 18 studies from 2020 to 2024.

Study location

The analysis of the most researched regions in Brazil revealed that, out of 102 studies, the highest frequency of research activity was concentrated in the southern region of the country, namely in Rio Grande do Sul (20%), Paraná (19%), Santa Catarina (8%), and São Paulo (8%) states. Additionally, some studies were also conducted in the northern Brazilian region—Amazonas (8%) and Pará (7%) states (Fig. 1). The remaining percentage is distributed across the other Brazilian states in fractions of less than 4%.

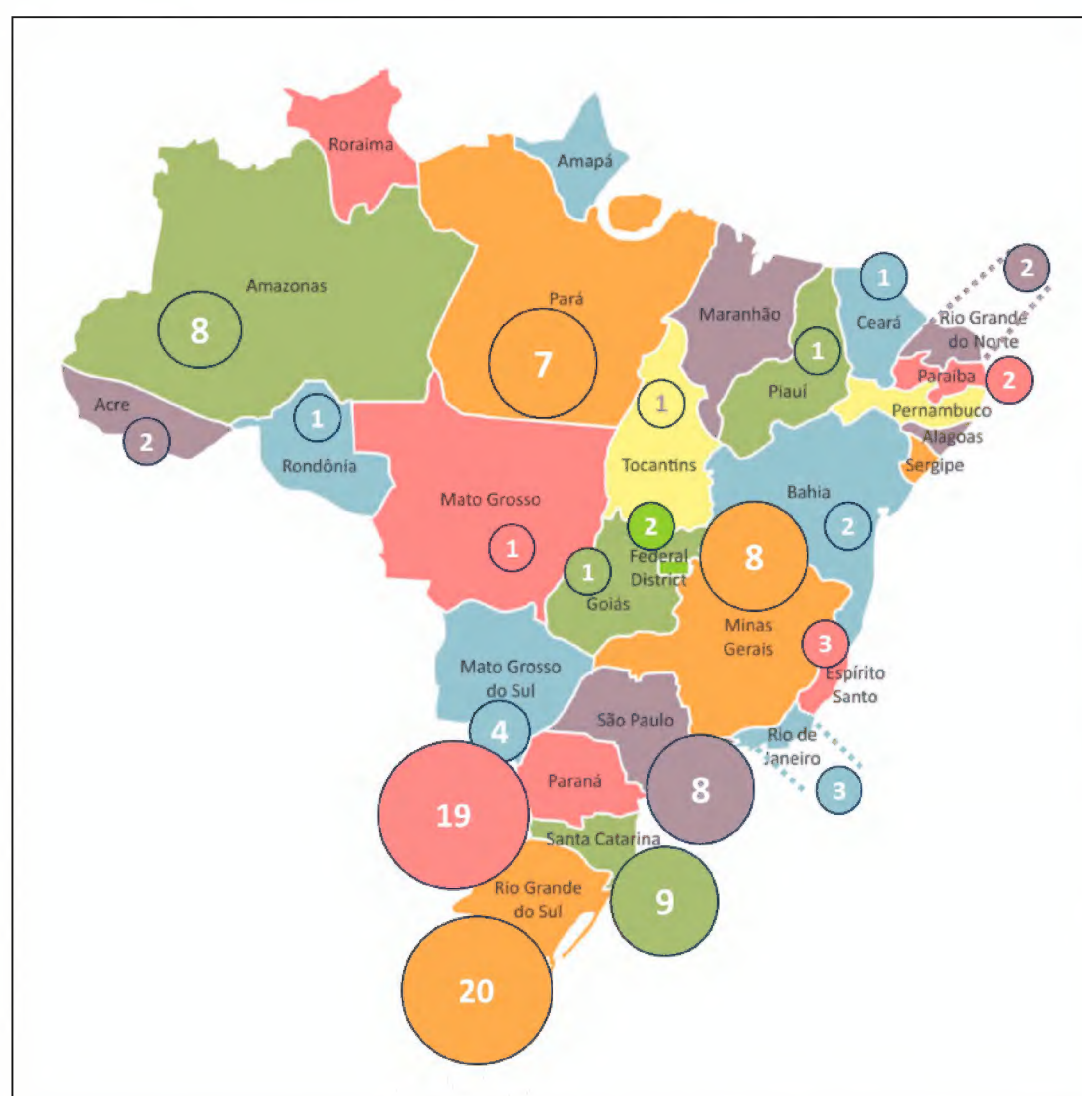


Figure 1. Distribution of the evaluated studies across the different Brazilian states (n = percentage (%) of studies per state).

The studies conducted in the southern region were mostly focused on agricultural land, while the ones conducted in the north had a higher percentage of trials in natural cover. Notably, the investigations emphasizing natural cover vegetation were carried out in the Brazilian area characterized by the Amazon Rainforest. The majority of the other studies were conducted in regions with the highest levels of agricultural activity.

According to EMBRAPA and FAO (OECD-FAO 2017), the Brazilian regions with the most intense agricultural activity are the central and southern states, showing a cropping frequency (number of times a crop is planted on the field during the course of a year) of 1.25–1.70 and 1.00–1.25, respectively. Although central and southern Brazil have the highest agricultural activity, studies are not strictly aligned with these areas. This discrepancy suggests that the study locations may not be directly aligned with the primary agricultural zones. It is likely that the studies were conducted in accessible arable, grassland, or natural cover regions near the universities or organizations overseeing the research.

When analyzing the results observed on the density of the different organism groups according to the various evaluated variables, it became clear that organisms such as earthworms and collembolans respond distinctly to the same variable.

Land use

Earthworm density on average did not show large differences between the different land uses (Fig. 2A). The average density in natural cover, arable fields, and grassland was 158 (± 726), 107 (± 310), and 134 (± 306) organisms m^{-2} , respectively, potentially showing that the less human-impacted habitat improves the population's ability to thrive.

Collembola showed the highest average densities for natural cover, arable fields, and grassland of 2,963 ($\pm 6,022$), 18,660 ($\pm 32,167$), and 191 (± 651) ind. m^{-2} , respectively (Fig. 2B). However, when not considering the clear outliers in the analysis (Culik et al. 2002; Mussury et al. 2002; Pompeo et al. 2016) due to values that are excessively high or low, the average density per m^2 was 1,645 ($\pm 2,690$), 849 ($\pm 1,169$), and 3,143 ($\pm 6,156$) in arable land, grassland, and natural cover, respectively.

These results are partially in line with the earthworm observations, as the lack of human intervention led to higher population densities (arable land or grassland versus natural cover). When analyzing the results from de Moraes et al. (2010) and Peres et al. (2013), which investigated the three land occupation filters at the same time, the collembolan average density per m^2 was 1,400 (± 872), 784 (± 0), and 2,888 ($\pm 2,744$) in arable land, grassland, and natural cover, respectively. These results demonstrate the same trend as observed with the above organism groups, with lower springtail densities observed in grassland and the highest in natural cover habitats.

Soil mite average density per m^2 was 1,281 ($\pm 4,532$), 324 ($\pm 1,077$), and 1,090 ($\pm 6,553$) in arable land, grassland, and natural cover, respectively (Fig. 2C). However, when not considering the study outliers in the analysis (Mussury et al. 2002; Silva et al. 2004) due to insufficient densities, the average densities per m^2 were 1,377 ($\pm 4,686$), 484 ($\pm 1,289$), and 1,143 ($\pm 6,712$) in arable land, grassland, and natural cover, respectively. If the study from Badejo et al. (2002), which found very reduced numbers of soil mites in arable fields and grassland,

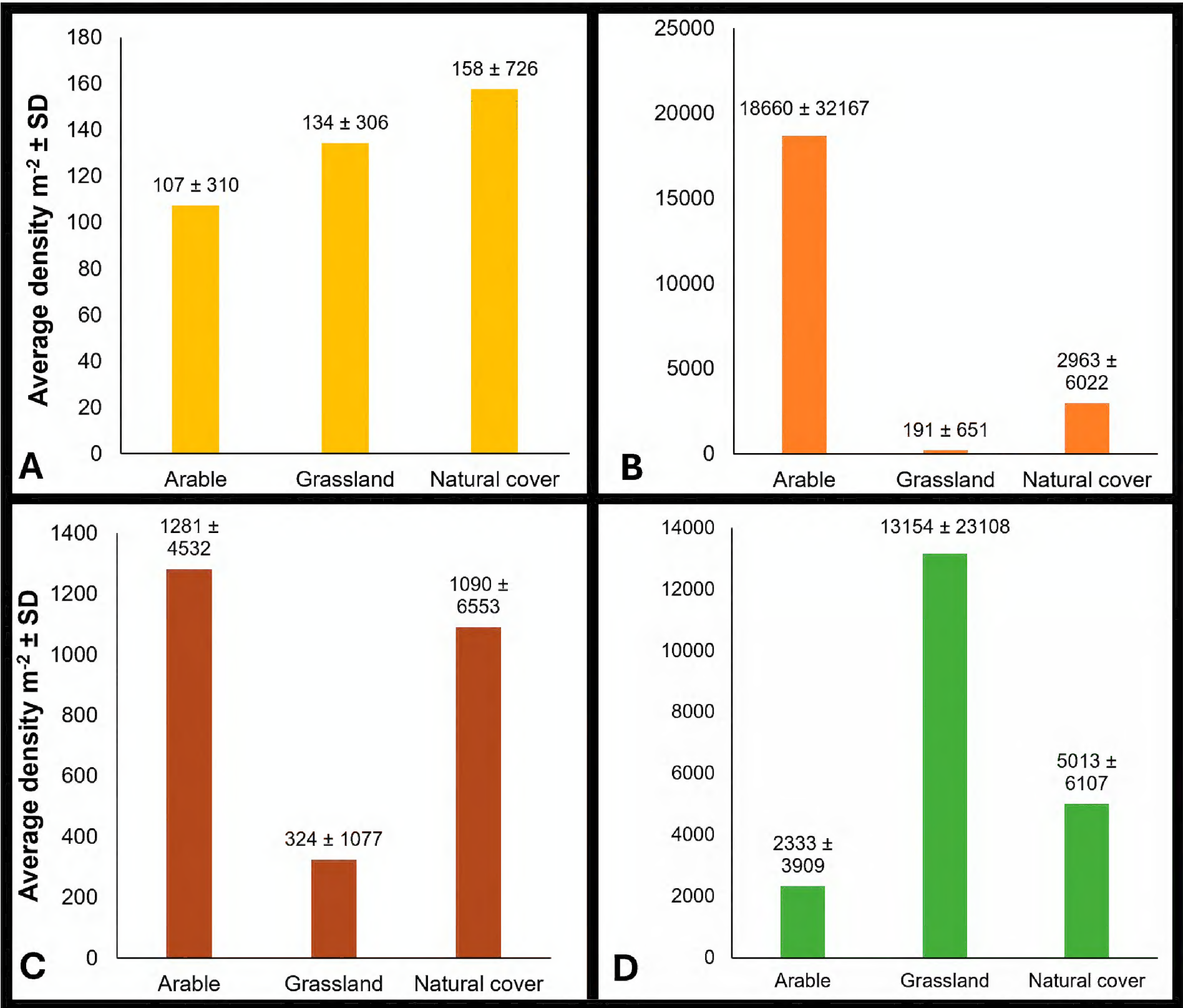


Figure 2. Variation in density of earthworms (A), springtails (B), soil mites (C), and enchytraeids (D) (ind. m⁻²) according to differences in land use.

is not considered in the evaluation, the overall average density is 8,494 (± 9,000), 1,741 (± 2,124), and 1,143 (± 6,712) ind. m⁻² in arable land, grassland, and natural cover, respectively. These results are not aligned with what was observed for earthworms and springtails, as there is an inverted trend in density values influenced by human intervention. When analyzing the results from individual authors who tested at least two types of land occupation in the same analysis, different results are observed. Chagas de Freitas et al. (2015) observed differences of around 70% between soil mite population densities in arable fields and natural cover habitats, with higher values in arable land. When comparing the following studies for the same land occupation, Menezes-Oliveira et al. (2021) and de Moraes et al. (2010) found differences in the opposite direction of 39% and 5%, respectively, with higher values in natural cover. São José et al. (2013) found almost no difference between arable fields and natural cover (1% difference). Guerra et al. (1982) and de Moraes et al. (2010) compared the densities of mite populations in arable fields and grassland and found differences of 8% and 200%, respectively, with higher densities in grassland.

The enchytraeid average density per m² was 2,333 ($\pm$ 3,909), 13,154 ($\pm$ 23,108), and 5,013 ($\pm$ 6,107) in arable land, grassland, and natural cover, respectively (Fig. 2D). However, it should be considered that there is a large impact on the overall numbers by Alexandre (2019). This study, when comparing grassland to natural cover, identified average densities of 43,886 ($\pm$ 23,158) ind. m⁻² and 22,580 ($\pm$ 9,199) ind. m⁻², while for arable land it found 5,546 ($\pm$ 6,625) ind. m⁻². On the opposite side of the scale, Peres et al. (2013) found 5 ($\pm$ 1), 0 ($\pm$ 0), and 2 ($\pm$ 0) ind. m⁻² in arable land, grassland, and natural cover, respectively. These results are aligned with what was observed for earthworms, as density values seem to be impacted by human intervention. When analyzing the results from studies that examined at least two types of land occupation in the same analysis, different results are observed. de Aquino et al. (2008) observed differences of around 5300% between enchytraeid population densities in arable fields—34 ($\pm$ 28) ind. m⁻²—and natural cover habitats—1,818 ($\pm$ 0) ind. m⁻². In the same land occupation comparison, Demetrio et al. (2020) found minor differences, only a 5% difference, but again in favor of the natural cover habitats. When comparing between arable land and grassland, Pompeo et al. (2016) found opposite differences, with higher densities of approximately 64% in grassland. For the only studies that compared the three land occupation scenarios—(Silva et al. 2006; Römbke et al. 2015; Römbke et al. 2021)—different trends were observed, but always with the same common denominator: lower enchytraeid densities in grassland. Römbke et al. (2015) and Römbke et al. (2021) found an enchytraeid average density per m² of 4,725 ($\pm$ 2,541), 3,950 ($\pm$ 2,994), and 6,329 ($\pm$ 3,262) in arable land, grassland, and natural cover, respectively. On the contrary, Silva et al. (2006) found an enchytraeid average density per m² of 24 ($\pm$ 58), 7 ($\pm$ 10), and 1841 ($\pm$ 1,092) in arable land, grassland, and natural cover, respectively. When analyzing both publications in detail, it became evident that not only does land occupation have a significant effect but also seasonal variation. When differentiating between rainy and dry seasons, the trend observed in the overall publications is also the same for these two studies. When pooling the results from both authors, during the dry season the densities in natural cover are 33% above those in arable fields. For the rainy season, the same trend is observed, with densities 63% above arable fields.

Overall, the patterns emerging across soil fauna groups suggest that apparent land-use effects are tightly linked with differences in land management intensity, climate gradients, and sampling biases among studies. Natural cover consistently supports higher densities of earthworms, collembola, and enchytraeids, but this trend becomes less clear—or even inverted—for soil mites, highlighting how taxon-specific responses can interact with local edaphic conditions such as soil texture, organic matter content, and pH. The considerable discrepancies resulting from outliers and uneven sampling designs across studies highlight that methodological heterogeneity poses a significant challenge in interpreting macroecological trends. In summary, while there is a general tendency toward higher densities in less disturbed soils for most groups, these findings should be considered within the context of underlying environmental variability and sampling biases, which can obscure or even invert anticipated land-use effects.

Seasonal variation

From all the studies conducted in the dry season, independently of the location (dry and rainy seasons vary according to the study location), earthworms were found on average at 202 (± 774) ind. m⁻². In contrast, during the rainy season, earthworm numbers decreased to 126 (± 318) ind. m⁻² (Fig. 3A). It is important to note that these figures are not directly correlated, as the average was derived from a comprehensive analysis of studies conducted under similar conditions. In a more direct comparison, in studies in which the authors sampled during both seasons using the same method and in the same parcels, several authors reached independent conclusions. Brown et al. (2003b) found an earthworm population average density of 66 (± 116) and 184 (± 289) ind. m⁻² in the dry and rainy seasons, respectively. The same author, in a different study (Brown et al. 2003a), encountered an earthworm population average density of 165 (± 492) and 262 (± 585) ind. m⁻² in the dry and rainy seasons, respectively. With similar results, Klenk (2010) encountered an earthworm population average density of 132 (± 34) and 344 (± 272) ind. m⁻² in the dry and rainy seasons, respectively. In an almost

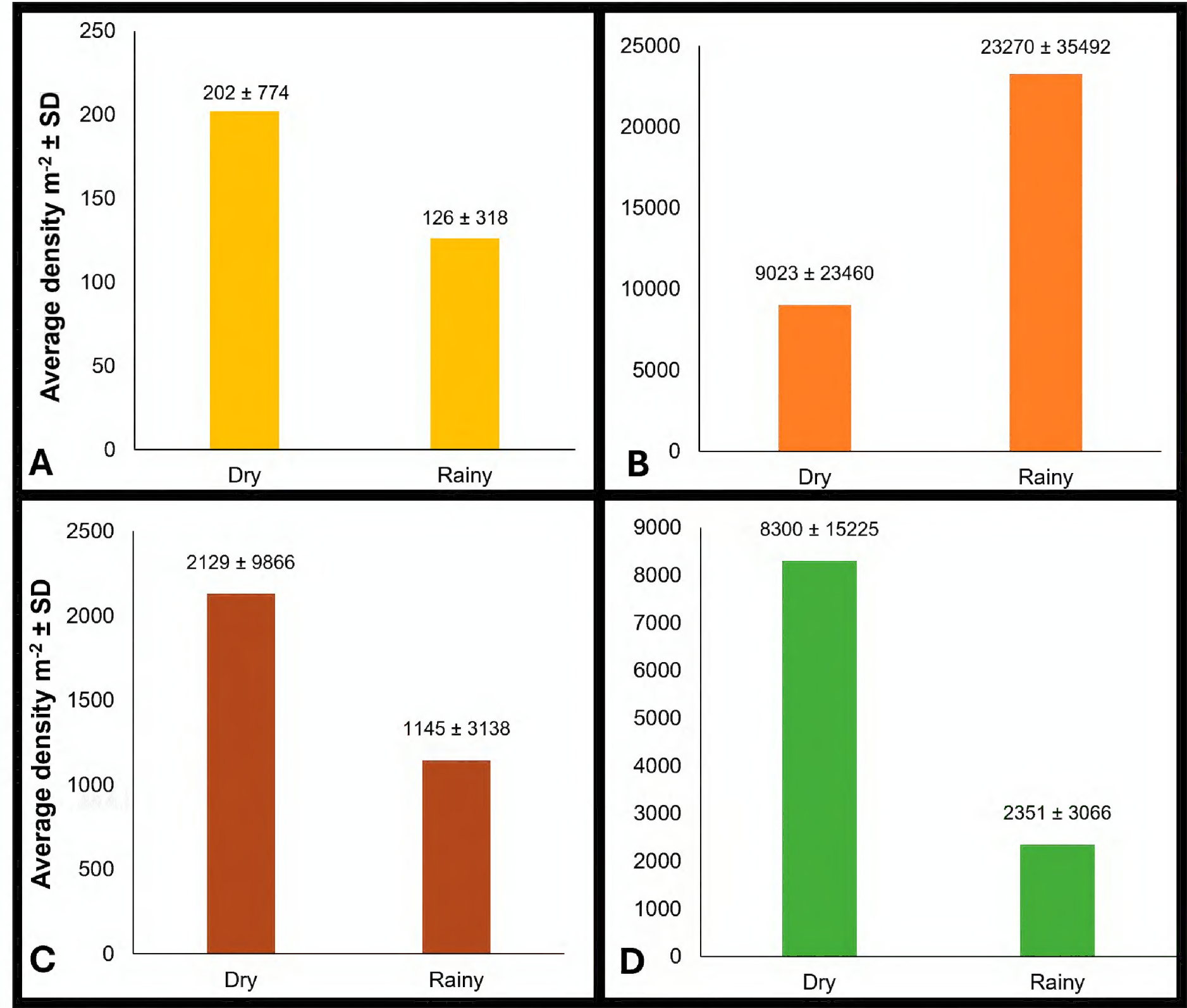


Figure 3. Variation in density of earthworms (A), springtails (B), soil mites (C), and enchytraeids (D) (ind. m⁻²) according to differences between dry and rainy seasons.

weighted result between the two seasons, Tanck et al. (2000), when studying the density of earthworms under the same methods, found no difference between seasons, with average densities of $45 (\pm 52)$ and $42 (\pm 52)$ ind. m^{-2} in the dry and rainy seasons, respectively. However, this may be due to the collection method selected—hand sorting. On the contrary, Nunes et al. (2006), while using the TSBF method as some of the previous authors, found earthworm populations with average densities of $18 (\pm 23)$ and $35 (\pm 67)$ ind. m^{-2} in the dry and rainy seasons in arable fields; $591 (\pm 727)$ and $209 (\pm 363)$ ind. m^{-2} in grassland; and $11 (\pm 18)$ and $6 (\pm 9)$ ind. m^{-2} in natural cover, respectively. From most of the publications analyzed, it can be concluded that the rainy season typically favors higher densities of earthworms in arable fields, grasslands, and natural cover habitats.

For the evaluated studies conducted in the dry season, Collembola population average density was $9,023 (\pm 23,460)$ ind. m^{-2} . During the rainy season, springtail numbers were on average $23,270 (\pm 34,592)$ ind. m^{-2} (corresponding to a 158% difference) (Fig. 3B). However, it should be taken into consideration that these numbers are not directly related, as the average was calculated based on the overall studies conducted in such conditions. In a more direct comparison, in studies in which authors sampled both seasons using the same method in the same parcels (Ferreira and Silva 2001; Soares and Costa 2001; Culik et al. 2002; Silva et al. 2016), the average density of springtails was $34,451 (\pm 43,673)$ and $50,430 (\pm 39,435)$ ind. m^{-2} in the dry and rainy seasons, respectively, still demonstrating an increase of around 46% toward the rainy season, although less markedly. When analyzing the findings from the various retrieved publications, some differences were observed. Culik et al. (2002) found a much smaller but opposite difference between seasons, with $77,500 (\pm 30,917)$ and $62,995 (\pm 33,977)$ ind. m^{-2} in the dry and rainy seasons, respectively. Ferreira and Silva (2001) found an average density of $12 (\pm 0)$ and $708 (\pm 0)$ ind. m^{-2} in the dry and rainy seasons, respectively. However, these values correspond to samplings in natural cover under high organic matter values (25–30%) and each on two consecutive years (dry season in 1997 and rainy season in 1998). Consequently, factors beyond seasonal variation may have influenced the density of springtails. Following a similar research approach, Soares and Costa (2001) found no springtails in the dry season and an average of $64 (\pm 64)$ ind. m^{-2} in the rainy season. On the contrary, Silva et al. (2016) found an average density of $25 (\pm 19)$ and $3 (\pm 0)$ ind. m^{-2} in the dry and rainy seasons, respectively. Although there is a noticeable difference in Collembola density between the two seasons, a closer analysis reveals fluctuations likely influenced by additional abiotic factors rather than being solely attributed to seasonal variation.

Regarding soil mite population density, for the evaluated studies conducted in the dry season, the average was $2,129 (\pm 9,866)$ ind. m^{-2} . In contrast, during the rainy season, soil mite numbers were on average $1,145 (\pm 3,138)$ ind. m^{-2} (54% difference) (Fig. 3C). These figures are not directly correlated, as the averages were derived from studies conducted under similar but not identical conditions. In a more direct comparison, studies conducted by Almeida (2016) and Azevedo et al. (2020), which utilized the same methodology across identical parcels during both seasons, revealed soil mite densities of $280 (\pm 758)$ and $720 (\pm 2,169)$ ind. m^{-2} in the dry and rainy seasons, respectively. This finding indicates a contrasting trend compared to the overall comparison. This discrepancy may be explained by the significantly different numbers

found by Menezes-Oliveira et al. (2021), who reported soil mite densities of 61,739 ($\pm 10,087$) ind. m^{-2} in the dry season. This author sampled in an arable field and in natural cover, but both sites had very high organic matter content (15%). This may have influenced soil mite density when compared to other studies. When excluding this study from the analysis, overall values of 560 ($\pm 1,117$) and 1,145 ($\pm 3,138$) ind. m^{-2} were observed in the dry and rainy seasons, respectively. Nevertheless, without Menezes-Oliveira et al. (2021), soil mite densities in arable land do not show the same trend, with 1,731 ($\pm 1,218$) and 1,482 ($\pm 3,683$) ind. m^{-2} in the dry and rainy seasons, respectively. As Menezes-Oliveira et al. (2021) did not analyze soil mite density in grassland, there was no impact on the overall soil mite density. When considering natural cover without Menezes-Oliveira et al. (2021), soil mite densities were 293 (± 907) and 779 ($\pm 2,098$) ind. m^{-2} in the dry and rainy seasons, respectively.

For enchytraeid population density, for the evaluated studies conducted in the dry season, the average was 8,300 ($\pm 15,225$) ind. m^{-2} . In contrast, during the rainy season, the enchytraeid numbers were on average 2,042 ($\pm 2,965$) ind. m^{-2} (Fig. 3D). It is important to note that these figures are not directly correlated, as the average was derived from a comprehensive analysis of studies conducted under similar conditions. In a more direct comparison, in studies in which the authors sampled during both seasons using the same method in the same parcels (Silva et al. 2006; Klenk 2010; Römbke et al. 2021; Bartz et al. 2023), the average density of soil mites was 3,052 ($\pm 3,475$) and 2,169 ($\pm 2,973$) ind. m^{-2} in the dry and rainy seasons, respectively. However, this trend is only justified by the significantly different numbers found by Römbke et al. (2021), with enchytraeid densities of 5,565 ($\pm 3,036$) and 4,925 ($\pm 2,900$) ind. m^{-2} in the dry and rainy seasons, respectively. When this last author is not considered in the analysis, overall densities of 260 (± 658) and 331 (± 825) ind. m^{-2} were observed in the dry and rainy seasons, respectively. The observed trend remains consistent across different land occupations, with the exception of grassland, where a higher number of individuals is recorded during the rainy season (a 49% increase). However, without the work from Römbke et al. (2021), the trend is completely the opposite, with higher densities during the rainy season for arable land with 10 (± 15) and 35 (± 74) ind. m^{-2} , grassland with 76 (± 90) and 113 (± 139) ind. m^{-2} , and natural cover with 1,397 ($\pm 1,012$) and 2,507 (± 840) ind. m^{-2} .

In summary, the contrasting seasonal patterns observed across earthworms, springtails, soil mites, and enchytraeids reflect a complex interplay of soil type, land management, climate gradients, and sampling biases (hand sorting versus TSBF) rather than a simple dry–rainy season dichotomy. Soils with higher organic matter and finer textures generally support larger and more stable populations, which helps explain unusually high densities in specific studies, particularly where organic-rich arable or natural cover soils were sampled. Climate gradients across Brazil further contribute to the observed variation, as the timing and intensity of dry and rainy seasons differ regionally, meaning that “dry” and “rainy” are not equivalent across studies in terms of soil moisture stress or biological activity. Finally, differences in sampling method (e.g., TSBF versus hand sorting), sampling year, and inconsistent reporting introduce substantial bias, at times reversing apparent trends when individual high-magnitude datasets are included or excluded. Together, these factors indicate that seasonal patterns in soil fauna abundance emerge not from seasonality alone but from

its interaction with environmental conditions, management history, and methodological variability, underscoring the need for harmonized sampling across climatic zones and soil-use systems.

Tillage practices

Regarding the impact of practicing tillage in arable land and its influence on the earthworm population, a clear trend was observed. While in arable fields where no tillage occurred, the authors reported an average of 77 (± 190) ind. m^{-2} (40 authors averaged density); in arable fields where tillage occurred, the density was 26 (± 56) ind. m^{-2} (Guerra et al. 1982; Krabbe et al. 1993; Brown et al. 2003b; Nunes et al. 2006; de Aquino et al. 2008) (Fig. 4A). When considering only the studies that compared the use versus the non-use of tillage in the same field (Guerra et al. 1982; Krabbe et al. 1993; Brown et al. 2003b; Nunes et al. 2006; de Aquino et al. 2008), the conclusions were similar. While in non-tillage fields there was an average of 97 (± 264) ind. m^{-2} , in fields with tillage the average was 26 (± 56) ind. m^{-2} . Both these values, from the overall collection

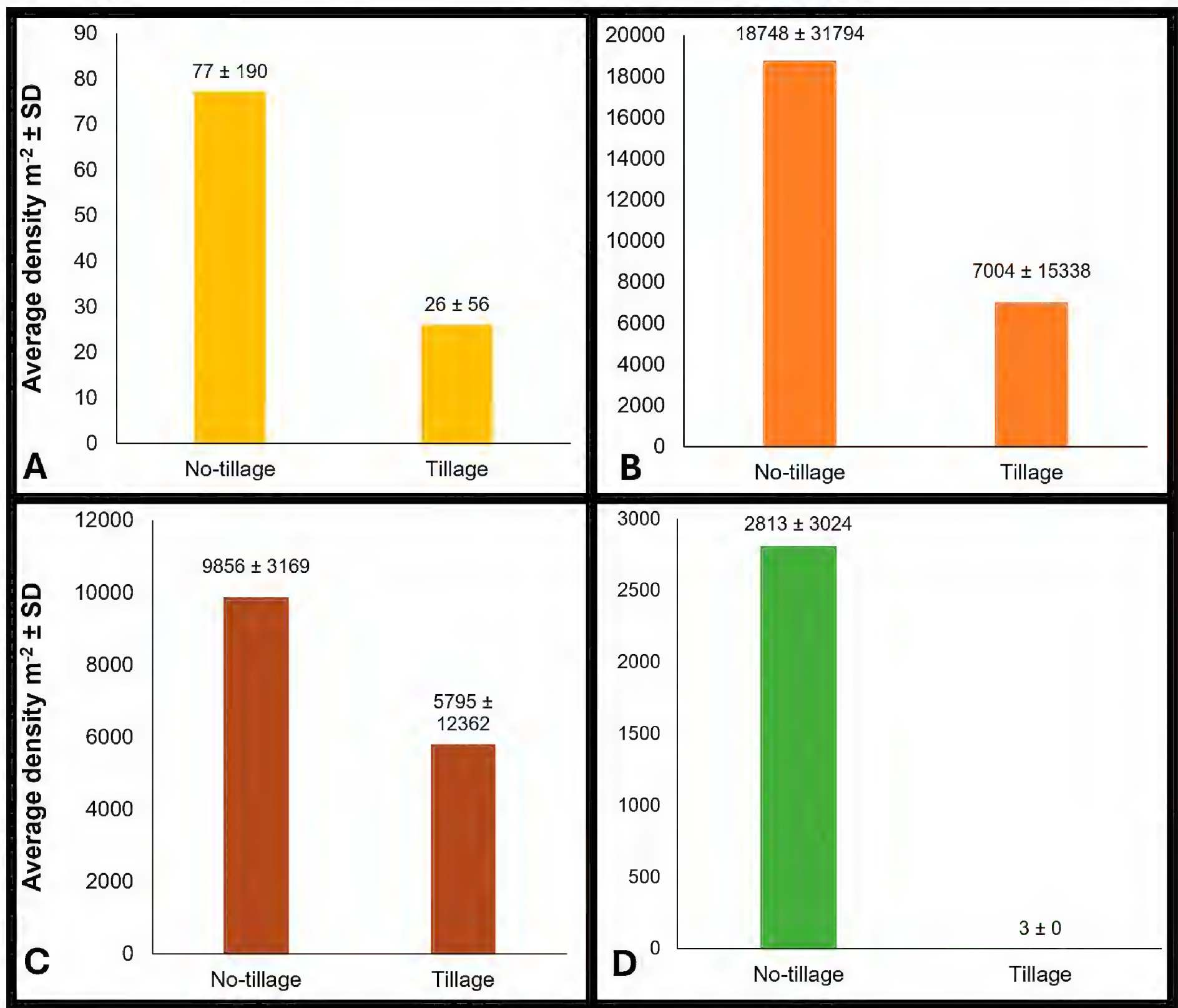


Figure 4. Variation in density of earthworms (A), springtails (B), soil mites (C), and enchytraeids (D) (ind. m^{-2}) according to differences between tillage and no-tillage crop systems.

of authors and the reduced number of contributors, demonstrate that the use of tillage as an agricultural practice can significantly impact earthworm populations, with a potential reduction of at least 67%. Brown et al. (2003b) not only investigated the impacts of tillage but also the interaction with the season (winter versus summer), revealing that tillage had a similar impact on earthworm density, resulting in reductions of 72% during the summer and 75% during the winter, irrespective of the season. Krabbe et al. (1993), while analyzing the impact of tillage, also found that both in spring and winter a reduction of 82% in earthworm density was observed independently of the timing. In the reviewed studies that compared the impacts of tillage and no-tillage practices within the same publication, no additional parameters were analyzed, aside from the seasonal aspect, to facilitate a more in-depth interpretation.

A distinct response was noted concerning the effects of tillage practices on the springtail population. While in arable fields where no tillage occurred, the authors found on average 18,748 ($\pm 31,794$) ind. m^{-2} (Guerra et al. 1982; Culik et al. 2002; Mussury et al. 2002; Heid et al. 2012; São José et al. 2013; Menezes-Oliveira et al. 2021); in arable fields where tillage occurred, the density was 7,004 ($\pm 15,338$) ind. m^{-2} (Culik et al. 2002; Heid et al. 2012; São José et al. 2013; Demetrio et al. 2020) (Fig. 4B). When considering only the authors that compared the use versus the non-use of tillage in the same field (Culik et al. 2002; Heid et al. 2012; São José et al. 2013), the conclusions were not the same, with 19,641 ($\pm 32,272$) ind. m^{-2} in fields where no tillage occurred and 18,097 ($\pm 21,305$) ind. m^{-2} in fields where tillage occurred. This observation should be regarded as an artifact of the average calculations, as each author identified significant differences in their individual analyses. Culik et al. (2002) found that tillage reduced the collembolan population by approximately 45%, while Heid et al. (2012) and São José et al. (2013) observed decreases of around 30% and 70%, respectively. When analyzing the impacts of sampling during different seasons together with the practice of tillage, some interesting results were obtained. Culik et al. (2002) sampled in the same study location during the four seasons and observed that while in autumn, spring, and winter the mean density of *Collembola* decreased by around 50% with the use of tillage, in summer there was no difference observed, with only 1% variation. On the contrary, São José et al. (2013) analyzed only summer and observed a decrease of 70% in springtail density per square meter.

Regarding the soil mite population, while in arable fields where no tillage occurred, the authors found on average 9,856 ($\pm 3,169$) ind. m^{-2} (São José et al. 2013; Almeida 2016), in arable fields where tillage practices were implemented, the density was 5,795 ($\pm 12,365$) ind. m^{-2} (Guerra et al. 1982; Mussury et al. 2002; São José et al. 2013; Menezes-Oliveira et al. 2021) (Fig. 4C). When considering the only author that compared the use versus the non-use of tillage in the same field (São José et al. 2013), the conclusions did not follow the same trend. Specifically, fields without tillage exhibited an average of 10,459 ($\pm 2,655$) ind. m^{-2} , while tilled fields recorded an average of 11,943 ($\pm 4,824$) ind. m^{-2} . However, it should be taken into consideration that after sampling, São José et al. (2013) analyzed the soil and highlighted that the samples were taken with different pH values. When tillage did not occur, with a pH between 6.0 and 6.5, there were 11,168 ($\pm 2,261$) ind. m^{-2} , while with a pH of 6.5–7.0, only 9,749 ($\pm 2,825$) ind. m^{-2} were found. The same trend occurred but with smaller differences in tilled soils,

with densities of 12,121 ($\pm 3,607$) ind. m^{-2} in soils with a pH value between 5.5 and 6.0 and 11,764 ($\pm 5,784$) ind. m^{-2} in soils with a pH value between 6.5 and 7.0. Therefore, the evaluation of the effect of tillage on soil mites should be considered carefully, given the limited number of studies that have explored this variable under comparable conditions and its effects on soil mite density.

In enchytraeid populations, while in arable fields with no tillage the authors found on average 2,813 ($\pm 3,024$) ind. m^{-2} (Silva et al. 2006; Demetrio et al. 2020; Römbke et al. 2021), in arable fields where tillage occurred, the density was 3 (± 0) ind. m^{-2} (de Aquino et al. 2008) (Fig. 5C). However, due to the low number of studies evaluating the density of enchytraeid populations after tillage (de Aquino et al. 2008), any comparisons regarding the impact of this parameter on organism density should be approached with caution. When analyzing the only study that evaluated both tillage and no-tillage practices (de Aquino et al. 2008), 44 (± 25) ind. m^{-2} were found in non-tilled fields, while 3 (± 0) ind. m^{-2} were found in fields with tillage. Although there is a limited number of available studies, the similarities with earthworms, coupled with the observed impacts on springtails and soil mites, suggest that this group is likely to be affected in a comparable manner.

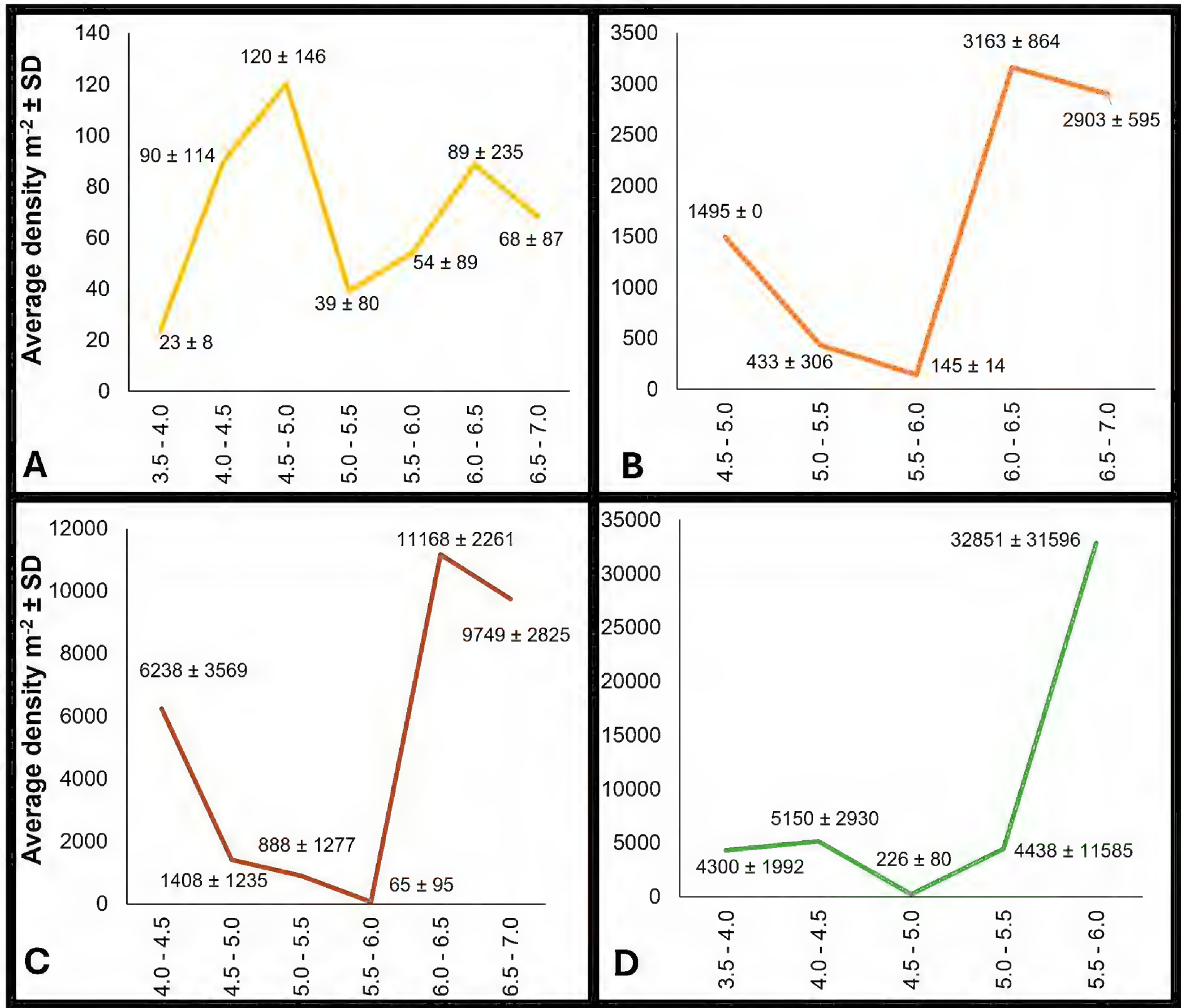


Figure 5. Variation in density of earthworms (A), springtails (B), soil mites (C), and enchytraeids (D) (ind. m^{-2}) according to differences in intervals of pH values.

Tillage practices significantly impact soil structure, the distribution of organic matter, and moisture retention—key factors upon which various groups of soil fauna rely to differing extents. In soils with inherently low organic matter or coarse texture, tillage magnifies habitat disruption, leading to sharper population declines, particularly for earthworms and enchytraeids, which are highly sensitive to physical disturbance (Betancur-Corredor et al. 2022). Land-management interactions—such as crop type, residue cover, and timing of operations—further modify these outcomes, explaining why season-by-season responses differ among studies. Furthermore, Brazil's diverse climate gradient results in significant variations in the biological impact of summer versus winter tillage, which are influenced by regional moisture regimes and soil temperature patterns. Overall, these data demonstrate that the contrasting responses of earthworms, springtails, soil mites, and enchytraeids to tillage arise from a combination of soil-type differences, land-management effects, climatic gradients, and methodological or sampling biases. As previously noted, differences in sampling scale, methodology, and inconsistent reporting (e.g., single-year comparisons, uneven sampling frequency, and variation in measured soil parameters) generate apparent contradictions in the presented data.

pH

On the evaluation of the pH (grouped) variation and its influence on the earthworm population density in arable land and grassland, no marked trend is observed, with a slight decrease in pH 3.5–4.0 (23 ± 8 ind. m^{-2}) and a small increase in pH 4.5–5.0 (120 ± 146 ind. m^{-2}). When separating between arable land and grassland, a slight trend starts to emerge for arable land. For the pH groups 4.0–4.5, 4.5–5.0, 5.0–5.5, 5.5–6.0, 6.0–6.5, and 6.5–7.0, the following densities per square meter were observed: $20 (\pm 12)$, $2 (\pm 2)$, $51 (\pm 88)$, $58 (\pm 92)$, $89 (\pm 235)$, and $68 (\pm 87)$ ind. m^{-2} , respectively, showing that higher pH levels might lead to an increase in earthworm density (Fig. 5A). It is essential to approach these results with caution, as the findings for the pH groups 4.0–4.5 and 4.5–5.0 in arable land are derived from the studies conducted by Almeida (2016) and Demetrio et al. (2020), respectively. The same would apply to the values between 5.5 and 6.0 and above 6.0, which originated from Bartz et al. (2013) and Bartz et al. (2009), respectively, showing limited representativeness of the entire Brazilian arable field. In grassland, the trend is slightly shifted to lower pH values, with densities of $23 (\pm 8)$, $107 (\pm 121)$, $137 (\pm 148)$, $19 (\pm 58)$, and $0 (\pm 0)$ ind. m^{-2} found for the pH levels of 3.5–4.0, 4.0–4.5, 4.5–5.0, 5.0–5.5, and 5.5–6.0, correspondingly. In contrast to arable land, the highest densities of earthworms are observed in pH levels ranging from 4.0 to 5.0. This conclusion is supported by the findings of several researchers, including da Silva et al. (2023), Pierri Castilho et al. (2016), Santo et al. (2023), Demetrio et al. (2018), Klenk (2010), and Ressetti (2006). Hence, earthworm abundances on grassland sites seem to be higher in lower pH values (4.0–5.0), while in arable land, earthworms seem to be more abundant in higher pH values (5.5–7.0).

For the influence of pH on the springtail population density in arable land and grassland, no clear trend is observed, with a slight decrease in pH 5.0–5.5 (433 ± 306 ind. m^{-2}) and 5.5–6.0 (145 ± 14 ind. m^{-2}) and an increase in pH 4.5–5.0 ($1,495 \pm 0$ ind. m^{-2}), 6.0–6.5 ($3,163 \pm 864$ ind. m^{-2}), and 6.5–7.0

($2,903 \pm 595$ ind. m^{-2}) (Fig. 5B). However, most likely this decrease in pH 5.0–6.0 is due to the publication by Alexandre (2019), where the author found only reduced numbers during winter in grassland for pH 5.0–5.5 of $42 (\pm 0)$ ind. m^{-2} and for pH 5.5–6.0 of $145 (\pm 14)$ ind. m^{-2} . On the opposite side, Rieff et al. (2016) for pH 4.5–5.0 and 5.0–5.5 found an average density of collembolans of $1495 (\pm 0)$ and $498 (\pm 282)$ ind. m^{-2} . The highest figures recorded can be attributed solely to a single study (São José et al. 2013) where $3,163 (\pm 864)$ and $2,903 (\pm 595)$ ind. m^{-2} were found in soil with a pH level of 6.0–6.5 and 6.5–7.0, respectively. The analysis of *Collembola* did not allow for a clear differentiation between grassland and arable land due to the insufficient number of studies to adequately represent each land-use category.

For soil mite population density in arable land and grassland, no consistent trend is observed, with a slight decrease in pH 5.0–5.5 ($888 \pm 1,277$ ind. m^{-2}) and 5.5–6.0 (65 ± 95 ind. m^{-2}) and an increase in pH 4.0–4.5 ($6,238 \pm 3,569$ ind. m^{-2}), 6.0–6.5 ($11,168 \pm 2,261$ ind. m^{-2}), and 6.5–7.0 ($9,749 \pm 2,825$ ind. m^{-2}) (Fig. 5C). When only arable land or grassland is considered, the trend is similar, as in one publication the same authors investigated grassland and arable fields. Therefore, the analyzed results from the different authors, even if in different land occupation scenarios, complement each other. Almeida (2016) and São José et al. (2013) only studied the effects of pH changes in arable fields. Likewise, Badejo et al. (2002) and Rieff et al. (2016) only studied the effects of pH variations in grassland. From the overall results, it could be concluded that soil mite densities tend to be higher at higher pH levels or around 6.0–7.0. However, due to the variability observed, allied to the high densities also found in lower pH levels ($6,238 \pm 3,569$ ind. m^{-2}) (Almeida 2016), this trend seems to be an artifact of the study conditions and location.

The analysis of enchytraeid population density in arable and grassland environments also reveals no consistent trend. Notably, there is a slight decrease in pH 4.5–5.0 (226 ± 80 ind. m^{-2}) and an increase in pH 3.5–4.0 ($4,300 \pm 1,992$ ind. m^{-2}), 4.0–4.5 ($5,150 \pm 2,930$ ind. m^{-2}), 5.0–5.5 ($4,438 \pm 11,585$ ind. m^{-2}), and a pronounced difference at pH 5.5–6.0 ($32,851 \pm 31,596$ ind. m^{-2}) (Fig. 5D). When solely arable land is considered, de Aquino et al. (2008) and Silva et al. (2006) found similar densities of $44 (\pm 25)$ and $30 (\pm 45)$ ind. m^{-2} in soil pH of 5.0–5.5. In soils with pH values between 3.5–4.0 and 4.0–4.5, Römbke et al. (2021) found on average $4,300 (\pm 1,992)$ and $5,150 (\pm 2,930)$ ind. m^{-2} , respectively. However, while the first two publications were conducted in the same state (Mato Grosso do Sul) and in the same research station, Römbke et al. (2021) conducted their research in an EMBRAPA research station in Amazonas. When solely grassland is considered, Alexandre (2019), Klenk (2010), and Silva et al. (2006) found discrepant values. While Alexandre (2019) found densities of $33,106 (\pm 7,640)$ and $49,276 (\pm 26,231)$ ind. m^{-2} at pH 5.0–5.5 and 5.5–6.0, respectively, Silva et al. (2006) only found $10 (\pm 11)$ and $0 (\pm 0)$ ind. m^{-2} in the same intervals, correspondingly. Klenk (2010) only studied the density of enchytraeids at pH 4.5–5.0 in arable land and observed an average density of $226 (\pm 80)$ ind. m^{-2} . Upon analyzing the various parameters of these three publications and their potential influence on the density of enchytraeids, it became evident that location was the only significant variable observed: Alexandre (2019) conducted the study in the state of Santa Catarina, Klenk (2010) in the state of Paraná and Silva et al. (2006) in the state of Mato Grosso do Sul.

Overall, the apparent differences between arable land and grassland—such as earthworms showing higher densities at lower pH in grasslands but higher densities at neutral pH in arable soils—highlight how soil chemical conditions interact with management regimes, including pH corrections, vegetation type, and disturbance intensity. This mirrors the potential acid tolerance of organism populations across the Brazilian region. Additionally, many of the observed trends were disproportionately influenced by single studies or research stations with limited geographic representation, thereby amplifying artifactual patterns. Differences in sampling season, extraction methods, and the uneven distribution of pH classes across land-use types also constrain the comparability of datasets.

OM

On the evaluation of the OM (grouped) variation and its influence on the earthworm population density in arable land and grassland, some fluctuations are observed, with a slight decrease around 3.5–4.0% OM (17 ± 24 ind. m^{-2}) and 5.5–6.0% OM (15 ± 9 ind. m^{-2}), and a small increase in 2.0–2.5% OM (146 ± 289 ind. m^{-2}). When splitting between arable land and grassland, some density peaks emerge for arable land. For the OM percentage groups 2.0–2.5 and 4.5–5.0, densities of $174 (\pm 333)$ and $87 (\pm 105)$ ind. m^{-2} , respectively, were observed (Fig. 6A). However, both of these peaks are attributed to a single study (Bartz et al. 2009), which was conducted in a coffee plantation and, as shown above in the pH evaluation, could have created a misleading trend in the data. Apart from these two marked density peaks, no clear trend is observed between earthworm population density and organic matter percentages in arable land. In grassland, there is no evident trend either, with densities of $0 (\pm 0)$, $57 (\pm 98)$, $71 (\pm 57)$, $0 (\pm 0)$, $44 (\pm 69)$, and $40 (\pm 45)$ ind. m^{-2} being found in the samplings with OM% levels of 0.0–0.5, 0.5–1.0, 2.0–2.5, 3.5–4.0, 4.5–5.0, and 5.0–5.5, respectively. For interpreting these results, it should also be considered that for each of the OM% intervals, only one study was considered. While studies have been conducted across the states of Santa Catarina (Bartz et al. 2014), Amazonas (Guerra et al. 1982), Paraíba (Guerra and da Silva 1994), and Rio Grande do Sul (De Santo et al. 2023), yielding relatively homogeneous results, the overall representativeness of a typical Brazilian grassland remains somewhat constrained.

For the springtail population density in arable land and grassland, some fluctuations are observed, with a slight decrease around 2.0–2.5% OM (498 ± 282 ind. m^{-2}) and a stable high-density population among the other OM% values—1.0–1.5 ($2,578 \pm 996$ ind. m^{-2}), 1.5–2.0 ($3,087 \pm 869$ ind. m^{-2}), and 2.5–3.0 ($2,908 \pm 489$ ind. m^{-2})—with an increase in the last assessed interval of 3.5–4.0% OM ($4,655 \pm 0$ ind. m^{-2}) (Fig. 6B). When separating between arable land and grassland, the density decrease is no longer observed, as it was associated with a study conducted in grassland (Rieff et al. 2016). In arable land, the springtail density for the intervals 1.0–1.5, 1.5–2.0, and 2.5–3.0% OM was $3,120 (\pm 780)$, $3,087 (\pm 869)$, and $2,908 (\pm 489)$ ind. m^{-2} , respectively. However, it is important to note that the data regarding arable land springtail density in relation to organic matter content are derived from a single study (São José et al. 2013). In grassland, the springtail density recorded for the organic matter percentages of 1.0–1.5, 2.0–2.5, and 3.5–4.0% was $1,495 (\pm 0)$, $498 (\pm 282)$, and $4,655 (\pm 0)$ individuals per square meter, respectively. This data suggests

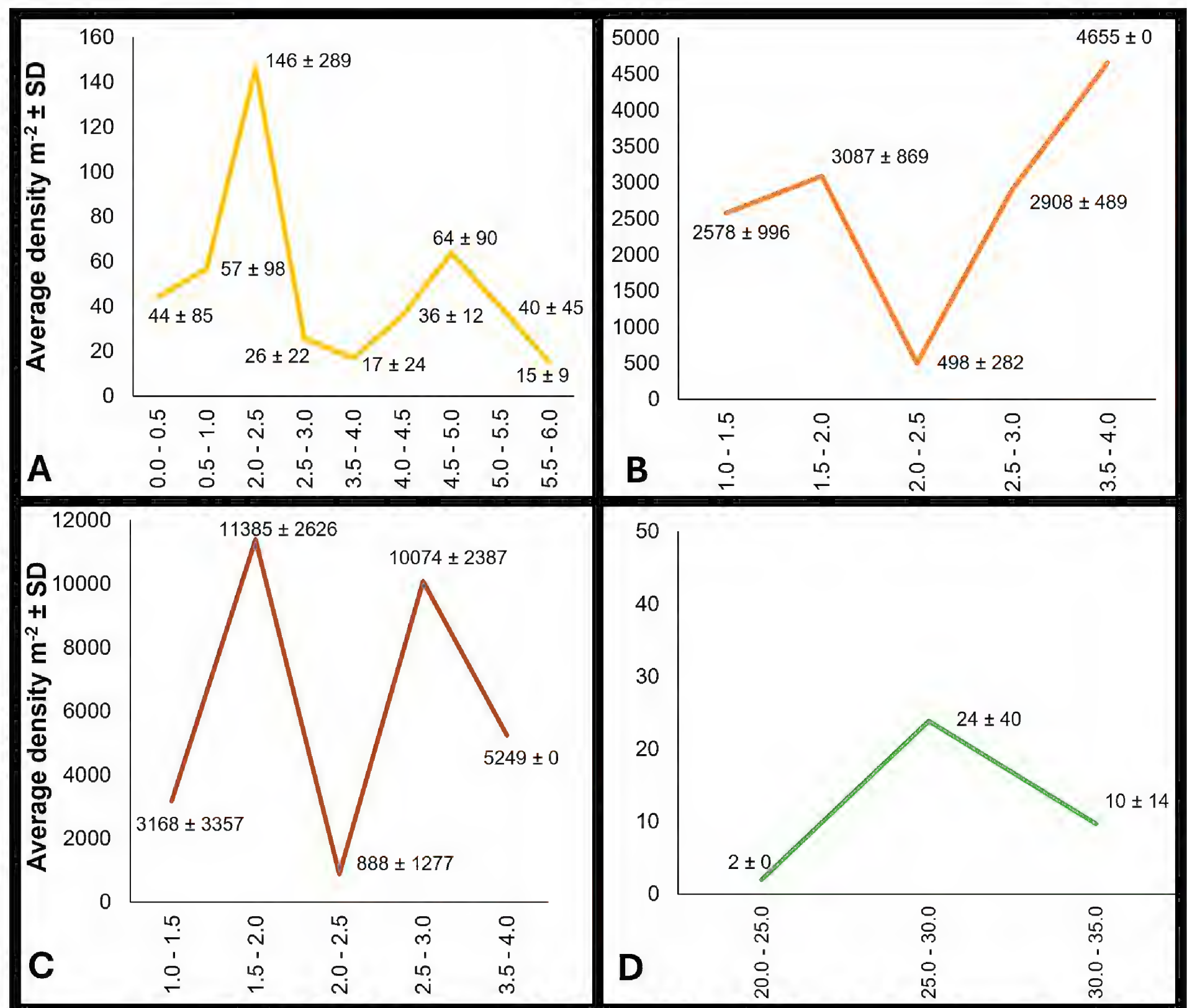


Figure 6. Variation in density of earthworms (A), springtails (B), soil mites (C), and enchytraeids (D) (ind. m⁻²) according to differences in intervals of organic matter percentages.

a notable decrease in density within the middle OM interval, contrasted by an increase at higher OM levels. The fluctuation observed between the intervals is attributed to a single study (Rieff et al. 2016), where the authors consistently observed low numbers of Collembola on six replicate samples, while in the 1.0–1.5% OM interval the values were much higher ($1,495 \pm 0$ ind. m⁻²).

On the evaluation of the OM (grouped) variation and its influence on the soil mite population density in arable land and grassland, some fluctuations are observed, with slightly lower densities around 2.0–2.5% OM ($888 \pm 1,277$ ind. m⁻²), a stable density of individuals between OM% of 1.0–1.5 ($3,168 \pm 3,357$ ind. m⁻²) and 3.5–4.0 ($5,249 \pm 0$ ind. m⁻²), and an increase in the intervals of 1.5–2.0% OM ($11,385$ ind. m⁻²) and 2.5–3.0% OM ($10,074 \pm 2,387$ ind. m⁻²) (São José et al. 2013) (Fig. 6C). When concentrating solely on arable land, the density peak observed in the overall evaluation no longer exists, with balanced numbers between 1.0 and 3.0% OM. When focusing only on grassland, the trend as initially observed is maintained, with lower density around 2.0–2.5% OM ($888 \pm 1,277$ ind. m⁻²) and an increase at 1.0–1.5% OM ($1,408 \pm 1,235$ ind. m⁻²) and 3.5–4.0% OM ($5,249 \pm 0$ ind. m⁻²) (Guerra et al. 1982; Rieff et al. 2016).

However, when analyzing additional variables, there is an observed effect from not only the OM percentage but also from other factors like seasonal variation. While Rieff et al. (2016) found $1,408 (\pm 1,235)$ ind. m^{-2} during the dry season at 1.0–1.5% OM, São José et al. (2013) found $8,449 (\pm 1,820)$ ind. m^{-2} . With respect to the other observed densities, a comparison of identical values among the same authors is not available. Therefore, all other peaks were observed in the rainy season by São José et al. (2013) and the lower density of $888 (\pm 1,277)$ ind. m^{-2} in the dry season by Rieff et al. (2016).

For the variability of OM and its influence on the enchytraeid population density in arable land and grassland, only one publication is available. Silva et al. (2006) found an average of $2 (\pm 0)$, $24 (\pm 40)$, and $10 (\pm 14)$ ind. m^{-2} in soil with an OM content of 20–25, 25–30, and 30–35%, respectively (Fig. 6D). When distinguishing between arable land and grassland, the author found $2 (\pm 0)$ and $36 (\pm 47)$ ind. m^{-2} in arable land with an OM content of 20–25 and 25–30%, respectively, and $4 (\pm 1)$ and $10 (\pm 13)$ ind. m^{-2} in grassland with an OM content of 25–30 and 30–35%, respectively. The same publication also evaluated the same parameter on natural cover, showing that with OM contents of 45–50, 50–55, and 55–60%, the enchytraeid density was $2,223 (\pm 1,231)$, $870 (\pm 0)$, and $1,667 (\pm 0)$ ind. m^{-2} . Considering that the percentage of organic matter is not markedly different from the ones found in the same publication for arable land and for grassland, it can be hypothesized that not only OM is influencing the abundance but possibly also other variables. As observed in this study, differences in enchytraeid densities are also noticed when focusing on seasonal variations, with 100 percent increases in the rainy season for OM% of 25–30, 30–35, and 45–50.

In general, because OM levels in the reviewed studies are strongly confounded with land management (e.g., coffee plantations, long-term grasslands, natural cover) and local soil properties, apparent density “peaks” frequently arise from single studies conducted under unique environmental or agronomic contexts, limiting the possibility of establishing patterns. The uneven distribution of OM classes across land-use categories and the predominance of single-study datasets for many intervals introduce substantial sampling bias, making it difficult to dissociate true ecological responses from artifactual patterns.

Types of soil (Brazilian classification)

Regarding the density of earthworms found according to variations in soil type (according to the Brazilian classification), some clear differences could be observed. When considering all evaluated studies, earthworms were found in higher densities in Nitossolo (519 ± 846 ind. m^{-2}), Latossolos (394 ± 534 ind. m^{-2}), Gleissolo (91 ± 50 ind. m^{-2}), and Cambissolo (85 ± 70 ind. m^{-2}). For the other types of soil sampled by the authors, the densities were all below 58 ind. m^{-2} (Fig. 7A). However, when the overall data are divided by the type of land occupation, it becomes evident that while in arable fields the type of soil with a higher density of earthworms was still Nitossolo (519 ± 846 ind. m^{-2}), followed by Gleissolo (119 ± 49 ind. m^{-2}), in grassland it was predominantly Latossolo (731 ± 532 ind. m^{-2}), followed by Cambissolo (75 ± 79 ind. m^{-2}). In natural cover, the type of soil with the highest density of earthworms was Cambissolo (97 ± 54 ind. m^{-2}), followed by Gleissolo (76 ± 43 ind. m^{-2}). Looking in even more detail, for the different land occupations, the biggest discrepancies are found

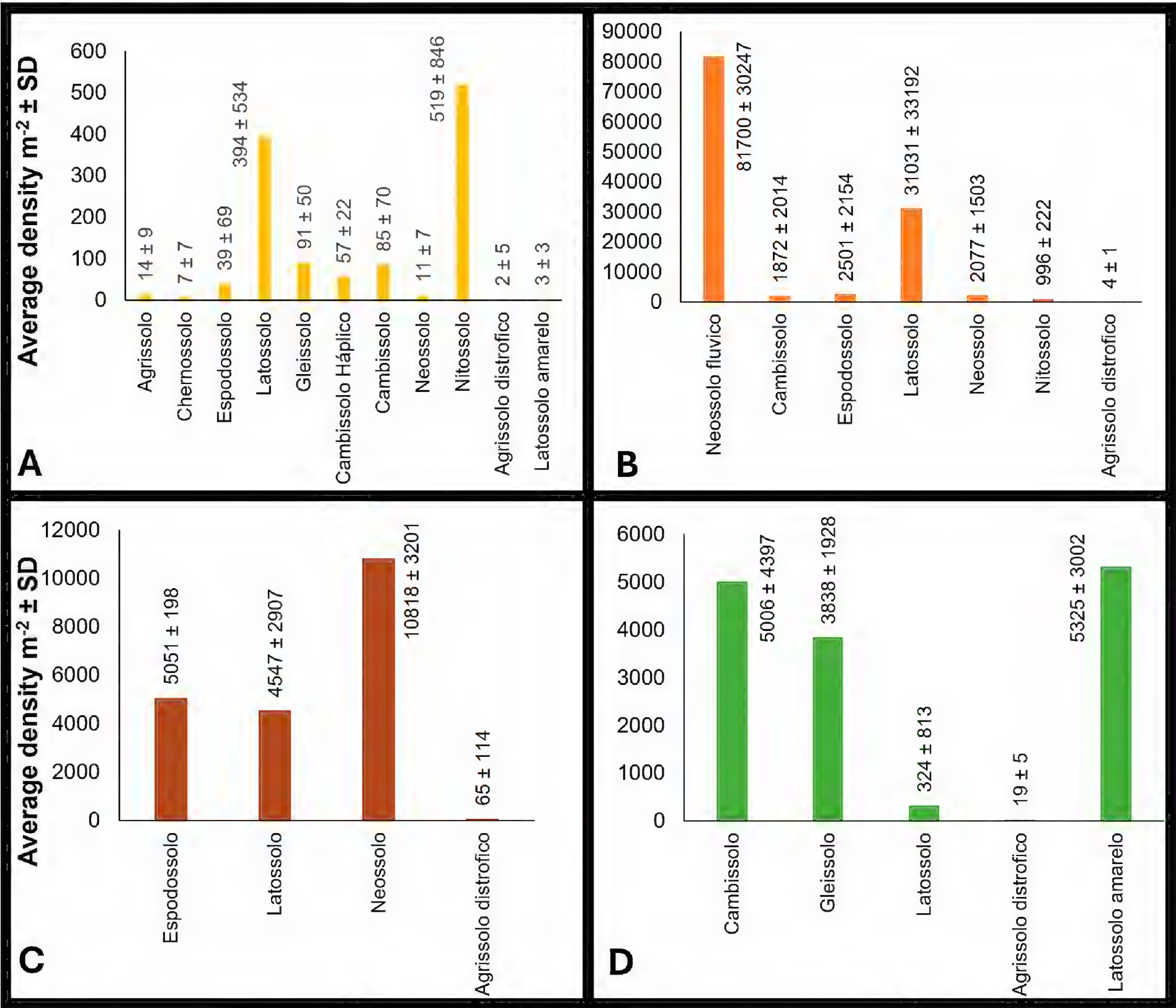


Figure 7. Variation in density of earthworms (A), springtails (B), soil mites (C), and enchytraeids (D) (ind. m^{-2}) according to differences in type of soil (Brazilian classification).

to be related to specific studies. Namely, in arable land, the highest numbers found in the states of Santa Catarina and Paraná in Nitossolo originated from the studies of Pandolfo et al. (2005) and Bartz et al. (2009), respectively, while the highest numbers in Paraná in Gleissolo were reported only by Römbke et al. (2009) but were obtained by hand sorting instead of TSBF or soil cores. In grassland, the highest numbers were obtained by Bussinguer (2018) with an average density of earthworms of 1,392 ($\pm$ 0) ind. m^{-2} . On the other hand, in similar conditions but in 1997, Dias et al. (1997) found densities of 9 ($\pm$ 3) ind. m^{-2} for grassland. In natural cover, the highest density found was again by Bussinguer (2018) with an average density of earthworms of 160 ($\pm$ 0) ind. m^{-2} . As a comparison between the three land occupations, and with the same type of soil—Cambissolo—Peres et al. (2013) found very similar values of earthworm densities between arable land (222 $\pm$ 51 ind. m^{-2}), grassland (259 $\pm$ 0 ind. m^{-2}), and natural cover (172 $\pm$ 70 ind. m^{-2}), showing that part of the discrepancies may be related to factors other than natural population variation. For example, while some authors have resorted to sampling techniques using soil cores or TSBF, others chose hand sorting. Likewise, variations in soil pH or OM may also

have played a role as described before in this publication. While it is not possible to correlate all these variables due to the lack of real replication, this might shed light on the variation found in terms of density of organisms.

Regarding the density of springtails found according to variations in type of soil, when considering all evaluated studies, springtails were found in higher densities in Neossolo flúvico ($81,700 \pm 30,247$ ind. m^{-2}) and Latossolo ($31,031 \pm 33,192$ ind. m^{-2}). The lowest densities of springtails were found in Argissolo (4 ± 1 ind. m^{-2}) (Fig. 7B). Moreover, when only the studies performed in arable fields are considered, the trend remains the same. When focusing on grassland, only two publications are available (Guerra et al. 1982; Peres et al. 2013), demonstrating that most springtails were found in Espodossolo ($4,655 \pm 0$ ind. m^{-2}), while Cambissolo (784 ± 0 ind. m^{-2}) showed lower numbers. However, it should be noted that as each type of soil originates from one single study, in principle, they are not comparable. Regarding natural cover, the trend was slightly different, with the highest density found in Cambissolo ($2,888 \pm 2,744$ ind. m^{-2}) followed by Neossolo ($1,290 \pm 1,824$ ind. m^{-2}). Overall, despite the observed trend, the differences cannot be considered fully comparable, as only Culik et al. (2002), Heid et al. (2012), and São José et al. (2013) had the same type of soil, and even among these authors a significant discrepancy in the results can be found.

With respect to the density of soil mites according to variations in type of soil, some clear differences could be observed. When considering all evaluated studies, soil mites were found in higher densities in Neossolo ($10,818 \pm 3,201$ ind. m^{-2}), Espodossolo ($5,051 \pm 198$ ind. m^{-2}), and Latossolo ($4,547 \pm 2,907$ ind. m^{-2}). The lowest densities of soil mites were found in Nitossolo (65 ± 114 ind. m^{-2}) (Fig. 7C). Moreover, when only the studies performed in arable fields are considered, the trend remains the same. When focusing on grassland, only two publications are available (Guerra et al. 1982; Badejo et al. 2002), showing that most soil mites were found in Espodossolo ($5,249 \pm 0$ ind. m^{-2}), while Nitossolo (65 ± 95 ind. m^{-2}) showed lower numbers. Regarding natural cover, it was not possible to analyze a trend, as only one publication was available. São José et al. (2013) found an average density of soil mites of $10,724 (\pm 260)$ ind. m^{-2} in Neossolo. This high density of soil mites found in natural cover has potentially influenced the overall numbers of organisms in this type of soil. However, all these comparisons between soils should be considered with caution, as for each type of soil only one publication was found. Specifically referring to soil mites, there are no studies where more than one type of soil is analyzed at the same time. Therefore, densities such as $10,830 (\pm 3201)$ ind. m^{-2} in Neossolos by São José et al. (2013) or $< 1 (\pm 0)$ ind. m^{-2} in Latossolos by Silva et al. (2016) are not considered indicative of the soil mite population sensitivity across the different soil types.

When considering all evaluated studies, enchytraeids were found in higher densities in Latossolo Amarelo distrófico ($5,325 \pm 3,002$ ind. m^{-2}), Cambissolos ($5,006 \pm 4,397$ ind. m^{-2}), and Gleissolos ($3,838 \pm 1,928$ ind. m^{-2}). The lowest densities of enchytraeids were found in Argissolos (19 ± 5 ind. m^{-2}) (Fig. 7D). Moreover, when only the studies performed in arable fields are considered, the trend remains similar, with the highest density of enchytraeids in Latossolo Amarelo distrófico ($4,725 \pm 2,541$ ind. m^{-2}). When focusing on grassland, only three publications are available (Silva et al. 2006; Peres et al. 2013; Römbke et al. 2015), showing that most enchytraeids were found in Gleissolos ($4,603 \pm 0$ ind. m^{-2}), while Cambissolos ($2,415 \pm 3,416$ ind. m^{-2}) and Latossolos (7 ± 10 ind. m^{-2})

presented lower numbers. Regarding natural cover, enchytraeids were found in higher densities in Cambissolos ($6,783 \pm 3,914$ ind. m^{-2}), Latossolo Amarelo distrófico ($5,925 \pm 3,293$ ind. m^{-2}), and Gleissolos ($3,647 \pm 2,112$ ind. m^{-2}). However, all these comparisons between types of soil should be considered with caution, as Römcke et al. (2015) was the only publication that compared different types of soil, with the other authors only evaluating one specific type where the samplings were conducted. For Römcke et al. (2015), enchytraeids were most abundant in Cambissolos, followed by Gleissolos. In parallel, in 2021, Römcke et al. (2021) evaluated the density of enchytraeids on natural cover in a Latossolo Amarelo distrófico and found an average of $5,925 (\pm 3,293)$ ind. m^{-2} .

In summary, soil types such as Latossolos, Cambissolos, Nitossolos, and Neossolos differ markedly in texture, structure, mineralogy, drainage, and nutrient status, all of which shape habitat suitability for different faunal groups. However, because most soil types in this dataset are represented by only one or a few geographically restricted studies—often employing different sampling methods (TSBF, soil cores, or hand sorting), conducted in distinct seasons, or embedded within contrasting land uses—observed “high” or “low” densities often reflect site-specific conditions rather than inherent properties of the soil class. Collectively, these limitations indicate that reported differences among soil types largely reflect the overlay of soil properties with management practices, regional environmental gradients, and uneven sampling design, rather than intrinsic biological responses to soil classification alone.

Conclusion

This study evaluates the population dynamics of earthworms, springtails (Collembola), soil mites, and enchytraeids across various land uses, soil types, soil properties, seasons, and farming practices in Brazil. While a precise Normal Operating Range for these four groups of organisms was not possible to determine, a wider picture of the influence of the evaluated parameters and their environmental impact on these organisms’ densities can be drawn, revealing differences in organism densities of up to three orders of magnitude. Whereas earthworm densities showed limited variation between land uses, the abundances of springtails, soil mites, and enchytraeids showed strong differences. Tillage practices on arable fields revealed a strong impact on abundances of all organism groups. Earthworm abundances do not seem to be majorly influenced by organic matter and pH in soil. Overall, research on Brazilian field populations of soil macro- and meso-fauna and the influential factors remains limited, specifically in northern Brazil (e.g., Caatinga and Cerrado regions). Our research highlights the need for a global collaboration between different stakeholders, academia, regulatory bodies, and industry in order to 1) align on methodologies and regional focuses of future research, 2) bring together a comprehensive understanding of the soil biodiversity, its natural fluctuation in space and time, and the influential factors behind it, and 3) contribute to the development of tailored SPGs for Brazil. A better understanding is needed on the soil functional implications of spatial and temporal soil organism fluctuations that are due to natural or anthropogenic stressors. This would contribute to an ecosystem services-oriented environmental policy that promotes reasonable agronomical soil management practices in the future.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

RP-S, FR and GE conceived and designed the research. RP-S and FR performed the literature review and compiled all data. RP-S, FR and IF analysed the data and prepared the graphical presentations. RP-S, FR and GE wrote the manuscript; other authors provided editorial advice.

Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Studies used for the different evaluated parameters

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Data type: docx

Explanation note: The data provided in the supplementary information is complementary to the evaluation of data as it provides a list of studies used for the different evaluated parameters and a list of the publications excluded from the data analysis.

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